REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0042

1. REPORT DATE *(DD-MM-YYYY)*
1/8/03

2. REPORT TYPE
Final

12/1/98 - 11/30/00

4. TITLE AND SUBTITLE
Electric Micropropulsion

01-16-03P03:05 RCVD

5a. CONTRACT NUMBER
F49620-99-1-0076

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
SSL-5-01

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
AFOSR/PKA
801 Randolph Street, Room 732
Arlington, VA 22203-1977

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release;
distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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20030305 056

15. SUBJECT TERMS
Colloid emmitters, micropropulsion, Hall thrusters

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSC
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include are code)*

ELECTRIC MICROPROPULSION

01-16-03P03:05 RCVD

Final Report
AFOSR Grant no. F49620-99-1-0076
(12/1/98 – 11/30/00)

by

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Abstract

We report here results obtained from our research in two areas: fully kinetic modeling of the plasma in Hall thrusters, and fluid modeling plus time-of-flight experiments on cone-jet colloid emitters for micropropulsion.

1. **Introduction.** This grant had two objectives, corresponding to the two Tasks below:

Task 1. Computation of Electron Energy Distribution in Plasma Thrusters.
We propose to develop computational techniques to calculate the electron distribution function in low density plasmas with geometries and parameters which are realistic for application to Hall and ion thrusters. This effort will support general micro-engine work since miniaturization reduces the required number of grid cells and microthrusters will therefore be the first beneficiaries of this new theoretical tool. The benefits will include improved diagnostics and more realistic performance modeling of future microthrusters designs, as well as the ability to calculate cross-field electron transport properties from first principles.

Task 2. Basic Studies on Colloidal Thrusters
We propose to construct physically-based models of the operation of colloidal engines, and to use them in support of laboratory studies on the optimization of these thrusters. The results will be used for the design of a microfabricated colloidal engine cluster, with the goal of reducing both, operating voltages and mass/power, without compromising performance.

We report here the results of our work under these tasks mainly by reference to (attached) publications and student Theses.

2. **Computation of Electron Energy Distribution in Plasma Thrusters.** Previous to this work, the state of the art in the modeling and simulation of Hall thrusters was represented by the model developed by J.M. Fife [1], also of our laboratory. In that model, designated as a Hybrid Particle-in-Cell (PIC) model, heavy particles were tracked kinetically in two dimensions (r – z in an axisymetric geometry), while electrons were treated as a fluid characterized by Boltzmann equilibrium and constant temperature along $\vec{B}$ lines only. Conservation equations for the electrons, were solved in the cross-field direction, and quasineutrality was assumed everywhere. This approach yielded valuable insights on many aspects of the Hall discharge, but was limited by the electron-fluid approximation too. For example, the electrons were implicitly assumed to be Maxwellian and isotropic, despite the strong magnetization and the large values of E/n_e, which tend to drive the plasma to be anisotropic and non Maxwellian, at least in some regions. The quasi-neutrality assumption also made it more difficult to study in detail the near-well regions and the plasma-wall interactions which are known to strongly affect plasma behavior.

In view of these challenges, we evaluated several possible approaches for extension of the theory, and selected a fully kinetic PIC model, where both electrons and heavy species are explicitly tracked. This work was carried out by James Szabo as his Doctoral dissertation [2], which must now be regarded as the current state of the art in this field.

The full PIC description is powerful, but it also introduces several execution difficulties. The wide disparity of time scales (from plasma time to neutral flow time) is accommodated through a combination of numerical techniques, including an artificially increased permittivity (ε_o), which also increases the Debye length scale, a reduced mass ration m_i/m_e,

and modified collision cross-sections. These modifications are used in combinations which permit recovery of true physics for most effects of interest (one exception is the thickening of sheaths, which however, appears to have only minor effects, given their smallness). The model still assumes axial symmetry, so that anomalous transport induced by azimuthal drift oscillations is not reproduced. The initial application has been to our 50 W Hall thruster [3] which is of the TAL type, and is fully documented in the enclosed Thesis by J. Szabo (Ref. 2). This work was later the basis for a successful proposal to NASA aimed at developing advanced models applicable to high voltage and two-stage Hall thrusters. Initial results on the high voltage effects were published in Ref. 4 (also attached).

3. **<u>Colloid Propulsion</u>**

The initial exploration by Vadim Khayms (Ref. 5) of a wide variety of options for high specific impulse micropropulsion gave us a strong indication of the potential of colloid thrusters, and opened up our research in this area. The principal motivations are associated with the intrinsically small unit thrust obtainable (of the order of 10^{-7} N per colloid emitter), the possibility of several types of precise control, and the ability to cluster large numbers of identical emitters using MEMS techniques [6].

The modeling work initiated by Khayms [5] was extended by P. Lozano, who also pioneered ion optics techniques for experimental Time-of-Flight work with these thrusters. This work is documented in Ref. [7], also attached. Theoretically, the model built upon earlier work by V. Khayms [5], who had formulated a steady , quasi 1D model and obtained some preliminary, but incomplete results. In particular, the current carried by the spray for a given voltage and flow rate was recognized to be an eigenvalue of the problem, but its calculation remained to be accomplished. In the model of [7], time evolution was explicitly introduced, which allowed the spray current to appear naturally as the cone-jet relaxed dynamically and electrically towards a steady state. Some numerical results were presented, which showed this relaxation process as an advancing front, behind which current had reached a spatially uniform profile. The simulation also showed instances of incipient jet breakup which agreed well with linearized stability analysis of this process. It was, however, realized that the numerical procedure was only marginally stable, and required unreasonably short time steps for stability (of order 10^{-2} – 10^{-3} smaller than even the very short charge relaxation times). There was also some dissatisfaction with the level of current to which the results appear to be converging. It was decided that a more critical look at the basic formulation would be needed, and this has been continued beyond the expiration of the Grant reported here. Some preliminary results of this revised model were given in Ref. [8] and complete results are now available and will appear shortly.

In terms of experiments, a first version of our new Time-of-Flight mass spectrometer was built, and verified through preliminary data on a low-conductivity solution. The TOF spectrometer is designed to operate on a principle similar to the classical Fizeau experiment to measure the speed of light: a short burst of spray (50 ns. to 30 μs. long) is allowed by a square opening probe of a normally-closed source gate. After a time delay selected by the operator (10-300 μs) a second gate, this time in front of a detector , is also pulsed similarly.

Only particles within a narrow range of times of flights $\left(t = \frac{L}{\sqrt{2\frac{q}{m}V}} \right)$ pass through both gates. The sequence is repeated periodically, and the mean detector current is recorded as a function of inter-gate time delay, producing a TOF spectrum. Although this was not implemented in the initial build, the sensitivity to accelerating potential V will be removed by interposition of an electrostatic "mirror" tuned to de-sensitize this variation in the desired range. In addition, the mirror doubles L, increasing sensitivity, and also provides a lateral spreading of the detected beam in response to variations in V among the beam particle. This can be used to create 2D spectra versus both, specific charge q/m and energy V.

The initial tests involved a Tri-Butyl Phosphate solution with a low expected specific charge of 127 C/kg. The measured spectrum showed a primary peak at 224 C/kg and a secondary peak at 1120 C/kg. The existence of two peaks confirmed independent data of Gamero [9], but the apparently high velocity (high q/m) of both peaks remained unexplained. It was pointed out by R. Dressler [10] that the finite spatial extent of the gating potentials could distort the measured spectrum, and with further investigation this proved to be the case in our tests. More recent work in the direction of eliminating this problem has been performed under a new AFOSR Grant, and highly accurate TOF spectrum, combined with retarding potential energy analysis, are now available and will appear shortly.

REFERENCES

1. John M. Fife, Hybrid PIC Modeling and Electrostatic Probe Survey of Hall Thrusters, MIT, Ph.D. Thesis, Sep. 1998.
2. James J. Szabo, Fully Kinetic Numerical Modeling of a Plasma Thruster, MIT, Ph.D. Thesis, January 2001.
3. Vadim Khayms, "Fifty Watt Hall Thruster for Microsatellites", Ch. 9 in Micropropulsion for Small Spacecraft, Prog. In Astronautics and Aeronautics, Vol. 187 (2000), M. Micci and A. Ketsdever Editors.
4. V. Blateau, M. Martinez-Sanchez, O. Batischev and J.J. Szabo, "PIC Simulation of High Specific Impulse Hall Effect Thruster". Paper IEPC-01-037, 27th IEPC Conference, Pasadena, CA, Oct. 2001.
5. Vadim Khayms, Advanced Propulsion for Microsatellites, MIT Ph.D. Thesis, Sep. 2000.
6. M. Martinez-Sanchez, J. Fernandez de la Mora, V. Hruby, M. Gamero and V. Khayms, "Research on Colloid Thrusters". Paper IEPC 99-104, 26th IEPC Conference, Kitakyushu, Japan, Oct. 1999.
7. P. Lozano and M. Martinez-Sanchez, "Jets and Sprays Emitted from Colloid Thrusters: Experiments and Modeling". 3rd International Conf. On Electric Propulsion, Cannes, Fr., Oct. 2000.
8. J. Carretero and M. Martinez-Sanchez, "Quasi-One-Dimensional Numerical Simulation of a Single-Emitter Collloidal Jet". Paper AIAA-2002-3812, 38th Joint Propulsion Conf., Indianapolis, IN, July 2002.
9. M. Gamero and V. Hruby, "Electrospray as a Source of Nanoparticles for Efficient Colloid Thrusters". J. of Propulsion and Power, 17, 977-987, (2001).
10. Rainer Dressler, private communication.